DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

High Resolution Numerical Modeling of Cohesive Sediment Transport

Tian-Jian Hsu
Civil and Environmental Engineering
Center for Applied Coastal Research
University of Delaware, Newark, DE 19716

Grant Number: N00014-09-1-0134

LONG-TERM GOALS

To develop a robust multi-phase, multi-class numerical modeling framework for both cohesive and non-cohesive sediment transport in the fluvial, estuarine and coastal environments.

OBJECTIVES

This study specifically focuses on numerical modeling of critical processes at small-scale (O(cm-100m)). Specific objectives are:

1. To develop turbulence-resolving numerical model of fine sediment transport in the oscillatory boundary layer in order to understand how turbulence-sediment interactions can determine fluid mud transport and the state of muddy seabed.

2. To develop a two-dimensional-vertical (2DV) numerical model based on Reynolds-averaged Navier-Stokes (RANS) equations and volume of fluid method for free-surface tracking to study mechanisms causing landward and seaward fine sediment transport in inter-tidal zones.

3. To develop 2DV-RANS modeling for wave-mud interactions in order to understand the competing effects between mud dissipation and shoaling in determining the resulting nonlinear wave propagation.

APPROACH

Cohesive sediment transport involves a variety of physical mechanisms including boundary layer processes (tidal and wave), gravity-driven flow, turbulence modulation, flocculation, non-Newtonian rheological behavior and consolidation (e.g., Mehta 1989; Winterwerp and van Kerstern 2004). A general modeling framework appropriate for a wide range of concentration needs to be based on multiphase flow theory. In this study, a fine sediment transprt modeling framework based on Equilibrium Eulerian Approximation (Ferry & Balachandar 2001) to the multiphase equations has been developed and extended to model various cohesive sediment transport processes. This fine sediment modeling framework is the basis of three numerical models developed for 1DV (one-dimensional-vertical), 2DV and 3D for different applications investigated in this study. In the Reynolds-averaged 1DV modeling, the dynamics of wave-supported gravity-driven mudflows has been studied (Hsu et al.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **2011**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **High Resolution Numerical Modeling of Cohesive Sediment Transport**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Civil and Environmental Engineering Center for Applied Coastal Research University of Delaware, Newark, DE 19716**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
FY10 Annual Reports of S & T efforts sponsored by the Ocean Battlespace Sensing S & T Department of the Office of Naval Research., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

2007; 2008). Efforts are also devoted to improve existing flocculation formulation with more robust parameterizations on fractal dimension and floc yield strength (Son & Hsu et al. 2008, 2009). New flocculation formulation is then adopted in the 1DV model to study the effect of flocculation and bed erodibility on cohesive sediment transport in a meso-tidal environment (Son & Hsu 2010a,b). In the Reynolds-averaged 2DV modeling, we further utilize a volume of fluid (VOF) code for free-surface tracking (Lin & Liu 1998) and investigate wave propagation over muddy seabed (Torres-Freyermuth & Hsu 2010). Recently, this 2DV-VOF code is also extended to simulate cross-shore fine sediment transport in intertidal flats. To greatly reduce the uncertainties in the turbulence closure for sediment-laden flow, a 3D highly accurate turbulence-resolving Navier-Stokes solver is extended to study the role of sediment-induced density stratification in determing the resulting fine sediment transport and bed state in the wave boundary layer (Ozdemir et al. 2010a, b).

WORK COMPLETED

1DV modeling of wave supported gravity-driven mudflow and the effects of flocculation on fine sediment transport in tide-dominant environment.

These parts of the investigation have been completed. Main findings are summarized in the report of FY09. Five journal papers are published, in press or currently under review.

2DV RANS-VOF modeling of wave-mud interaction

Ongoing studies supported by ONR to study wave-mud interaction at Louisiana shelf have revealed the role of direct dissipation and nonlinear wave-wave interactions in determining observed wave attenuation (Sheremet & Stone 2003; Elgar & Raubenheimer 2008). Our ongoing modeling work using 2DV-RANS-VOF wave model suggests, on horizontal bottom, low frequency wave energy similar to that of high frequency waves (Sheremet & Stone 2003), is transferred to sea-swell band and get dissipated (Torres-Freyermuth & Hsu 2010). On the other hand, for the case of sloping seabed, shoaling effect dominates and drains energy from sea-swell to low frequency band, consistent with field observation of Elgar & Raubenheimer (2008). Our model results suggest, however, comparing with results without mud, the presence of mud can still reduces the amount of energy transferring to low frequency band due to shoaling. Hence, there exists a competition between direct mud dissipation and shoaling process at muddy shelf. This problem is not only dependent on mud rheology but also flow depth and beach slope that deserves further numerical investigations. Essentially, without a complete understanding on the competing effects between bottom mud dissipation and shoaling in determining the wave energy evolution and dissipation, it is difficult to back calculate the bottom seabed properties from the observed wave field. A journal publication summarizing our numerical model development effort is published (Torres-Freyermuth and Hsu 2010). More recent investigation on the competing effects between bottom mud dissipation and shoaling over sloping seabed is underway. Numerical investigations are carried out for different beach slopes and mud availability.

3D two-way coupled turbulence-resolving simulation

A 3D numerical simulation tool for fine sediment transport in oscillatory boundary layer has recently been developed where all the scales of carrier flow turbulence are resolved without the uncertainties in turbulence closure (Ozdemir, Hsu and Balachandar, 2010, *J. Fluid Mechanics*, in press). For a given Stokes Reynolds number and settling velocity, we vary the available amount of sediment in the oscillatory boundary layer and observe four different flow regimes ranging from well-mixed sediment

in the wave boundary layer, formulation of lutocline and laminarization. Our ongoing work focuses on investigating the existence of these flow regimes and the lutocline dynamics for different settling velocities and Reynolds number.

2DV RANS-VOF modeling of cross-shore sediment transport at tidal flats

Conventional coastal modeling systems have difficulties in resolving the tidal front at the wetting and drying seabed and some numerical approximations, such as specifying a minimum artificial flow depth, are often adopted. However, it is not clear how such artificial numerical treatment can affect the accuracy of the results when tidal water's edge is of interest. Hence, a new numerical modeling approach for this problem is necessary. The 2DV RANS-VOF numerical model previously used for wave-mud interaction is revised for tidal flow. Our preliminary model results suggest the VOF approach is able to better predict the wetting and drying processes and resolve the turbid tidal water's edge. The only empirical parameter in the VOF approach that is sensitive to the water's edge process is the bed roughness height. However, bed roughness height is a much more physically-based parameter that can be measured with reasonable confidence.

RESULTS

The highlights of our study on cohesive sediment transport for FY10 is summarized here:

The state of muddy seabed in wave-dominant environment

One of the most important findings resulted from AMASSEDS indicates a significant reduction of bottom drag coefficient as tidal currents propagate over muddy seabed (Beardsley et al. 1995) due to attenuation of turbulence via fluid-mud-induced density stratification (Trowbridge & Kineke 1994). On the other hand, field and analytical studies on wave propagation over muddy seabed (e.g., Sheremet & Stone 2003; Dalrymple & Liu 1979) report increasing energy dissipation due to the presence of bottom fluid mud. The completely contradictory outcome of mud on the hydrodynamic dissipation for (tidal) currents and waves deserves more detailed investigation. Through ongoing ONR supports, we have developed a 3D turbulence-resolving simulation tool based on highly accurate pseudo-spectral scheme to study fine sediment transport in oscillatory boundary layer (Ozdemir et al. 2010a, b). Our simulation results reveal four distinct regimes of wave-induced fine sediment transport as sediment concentration increases (see Figure 1; Simulations are of Stokes Reynolds number Re_δ=1000 and settling velocity 0.5 mm/s). These different flow regimes are caused by sediment-induced density stratification on turbulence and mixing in the wave boundary layer. Specifically, we find that in the regime II of moderate concentration (10~50g/l), pronounced lutocline features appear at the top of the wave boundary layer. However, no significant damping of carrier flow turbulence (hence drag reduction) within the wave boundary layer is observed because damping mostly occurs around the top of wave boundary layer where turbulence production is already small (i.e., density stratification merely damps the nonlocal transport terms). Significant damping of carrier flow turbulence and laminarization are observed in regime III of higher sediment concentration (>>50 g/l). However, under such high concentration, rheological stress may become important to attenuate wave energy. Better understanding on the existence and main features of these flow regimes are critical to our predictive skill on the bed state and seabed properties.

Mechanisms causing landward and seaward sediment transport in a tidal flat

To understand the morphodynamics of intertidal zones, it is critical to study mechanisms causing landward and seaward sediment fluxes subjected to tidal flows and waves. The 1DV model for cohesive sediment transport is developed to quantify how sediment flux is associated with tidal skewness (asymmetry) (Son and Hsu 2010). In the literature, the settling-lag effect is considered to be the main mechanism causing landward transport (e.g., de Swart & Zimmerman 2009). On the other hand, the export of fine sediment through channel-runnel systems as well as the wave effects has been identified as one of the main offshore transport mechanisms in tidal flats. Field observations in the ongoing Tidal Flat DRI measure sediment pulse during flood and ebb tidal water's edge passage (A. Ogston, personal communication), consistent with several earlier studies in the European tidal flat (e.g., Christie et al. 1999). This provides important evidence to better understand landward and seaward transports in details, especially in terms of the contrast between the channel and the flat. Estuarine modelers in the ongoing Tidal Flat DRI (e.g., Chen et al. 2010) also identify export through channel as one of the missing mechanism in the existing coastal models, which prevent coastal models to capture the short residence time of river-delivered fine sediment. Because major transport occurs at tidal water's edge (e.g., Christie and Dyer 1998), there is a need to further investigate this issue with detailed numerical model that can resolve processes in the very shallow depth.

In the present two-dimensional-vertical (2DV) modeling, we primarily focus on idealized study in the cross-shore direction (the direction perpendicular to the tidal water's edge). Flow and sediment conditions investigated here are of a flat slope 0.0013, tidal range 4 m (similar to Willapa site), sediment settling velocity 0.5 mm/s, critical bed stress 0.15 Pa. Idealized standing-wave type tidal forcing of sine shape is specified (tidal asymmetry is zero). Two snapshots of the model results during flood and ebb are presented in Figure 2. Toward the middle of the flood (left panel in Figure 2), tidal velocity is strong and significant amount of sediment is suspended. The tidal water's edge induces strong velocity and sediment resuspension. This turbid tidal edge is a commonly observed feature in the intertidal zones (Christie and Dyer 1998). Right after the peak ebb velocity (right panel in Figure 2), ebb turbid tidal edge can be clearly seen. However, numerical model predicts different ebb tidal water's edge from that during flood. The ebbing flow leaves a thin water layer tail, which makes a more gradual transition of velocity at ebb water's edge. The asymmetry during the flood and ebb tidal edge can be more clearly identified based on the time series of velocity profiles and sediment concentration profiles at x=3900 m (Figure 3). The flood velocity induces a sediment concentration spike that is of high magnitude but short duration. One the other hand, the ebb velocity induces smaller concentration but with longer duration. Such asymmetry varies in the cross-shore direction and gives seaward transport in the lower flat and landward transport in the upper flat. More detailed investigation is underway to compare the present model results with the classic equilibrium and settling-lag paradigms (e.g., Friedrichs and Aubruy 1996).

IMPACT/APPLICATIONS

The present research efforts produce a numerical modeling framework for cohesive sediment transport for various applications in tide- or wave-dominated environment. Our model development efforts shall contribute the modeling capability in the ongoing ONR related research effort on Tidal Flat DRI, Wave-mud Interaction, Community Sediment Transport Modeling System (NOPP-CSTMS), Inlet and River Mouth DRI.

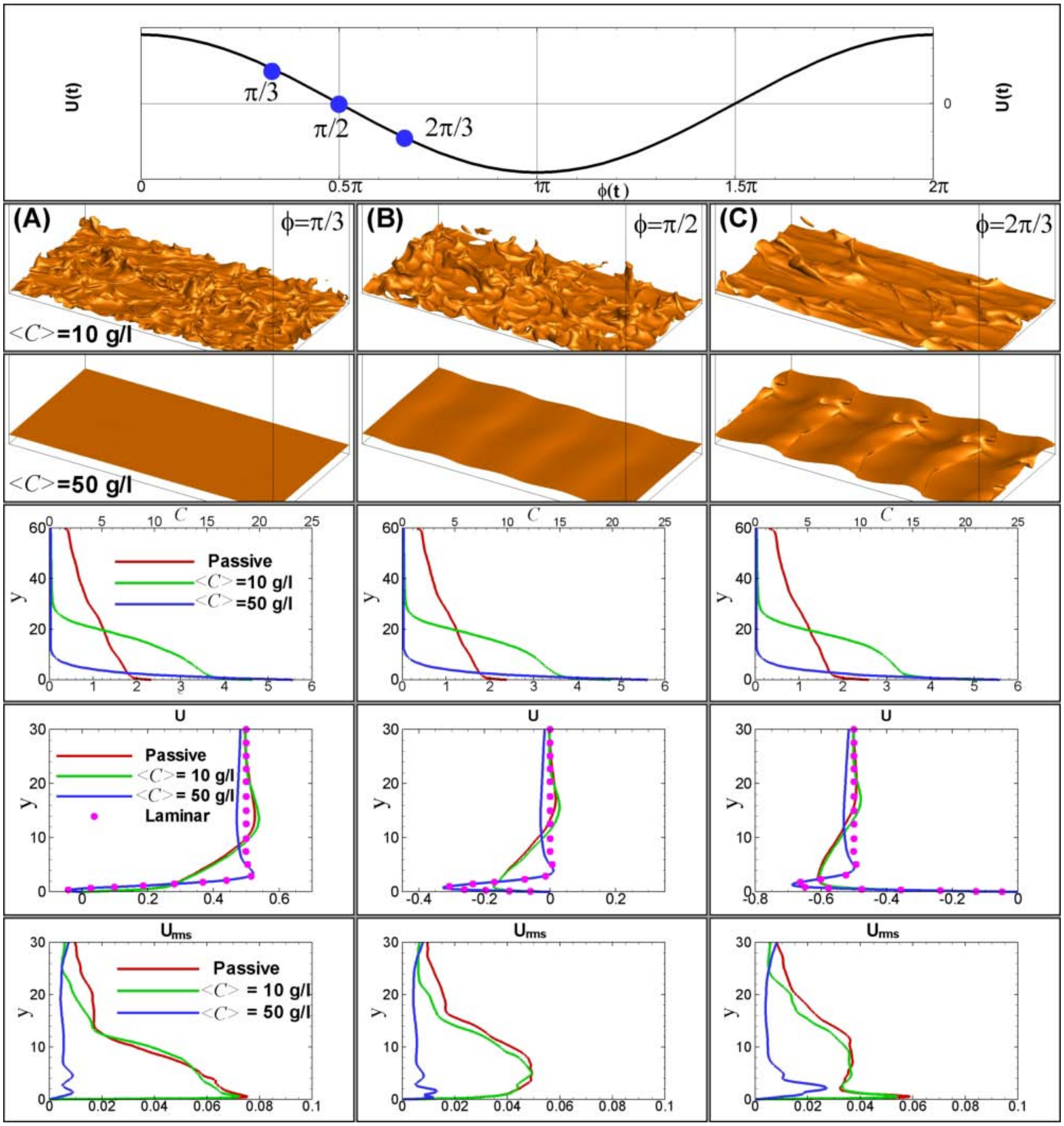

Figure 1: Simulation results for dilute (regime I), medium (regime II) to high concentration (regime III) cases (near bed concentration C≈O(0.1), 10, and 50 g/l, respectively). 1^{st} row: time-series of free-stream velocity and associated phases; The 2^{nd} and 3^{rd} rows: iso-surface of sediment concentration for regime II (C≈10 g/l), and regime III (C≈50 g/l) at three different phases. When concentration is large, flow laminarizes under wave crest but shear instability occurs during flow reversal (see 3^{rd} row). These features are very different from that of lower concentration where flow remains turbulent throughout the wave cycle (see 2^{nd} row). The 4^{th}, 5^{th}, and 6^{th} rows are averaged concentration, streamwise velocity and RMS turbulent velocity fluctuations profiles. Significant damping of turbulence due to sediment-induced density stratification causes laminarization of velocity and reduction of wave boundary layer thickness (compare blue with other curves). Magenta symbols in the 5^{th} row are theoretical laminar solution. In regime III, flow is almost laminarized by mud except during flow reversal. When concentration is O(100) g/l or more (Regime IV), flow is completely laminarized (not shown here). Re_{δ}=1000; W_s/U=0.0009.

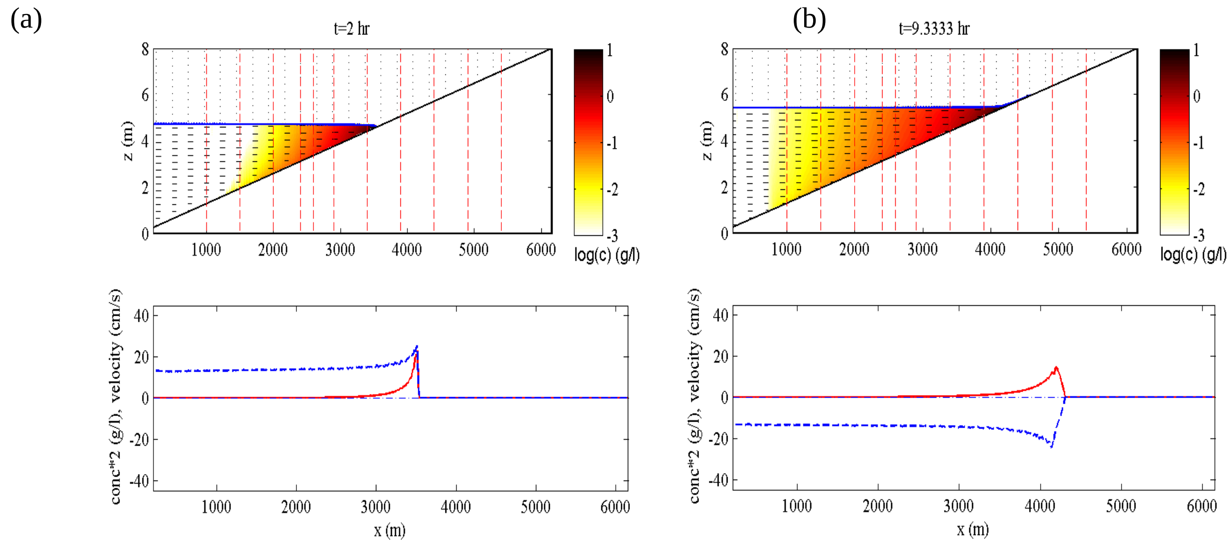

Figure 2: Snapshots of numerical model results during (a) flood tide and (b) ebb tide for flow field and sediment concentration (upper panel) and cross-shore distribution of flow velocity (dashed-blue curves) and sediment concentration (solid-red curves) at 2.5 cm above the bed (lower panel).

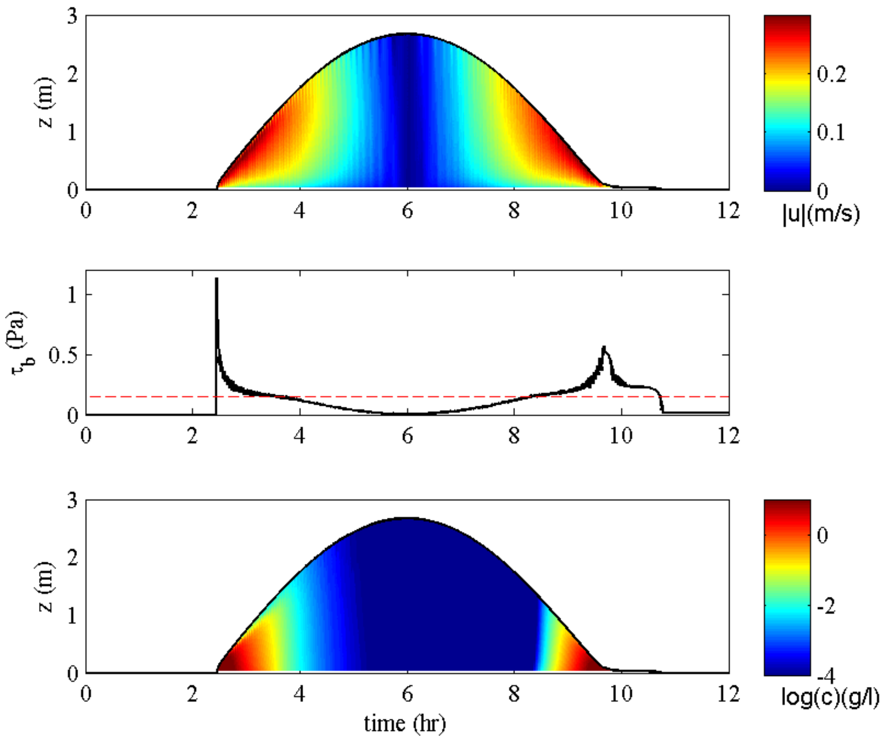

Figure 3: Time series of vertical profiles of cross-shore velocity magnitude (upper panel), bottom stress (middle panel) and sediment concentration (lower panel) at x=3900 m. The red-dashed line in the middle panel represents the critical bed stress (0.15 Pa) specified in this case.

REFERENCES

Beardsley, Robert C., Julio Candela, Richard Limeburner, W. Rockwell Geyer, Steven J. Lentz, Belmiro Castro, David Cacchione and Nelson Carneiro, (1995). The M2 tide on the Amazon shelf. *J. Geophys. Res.*, 100(C2), 2283-2319.

Chen, S.-N., W. R. Geyer, C. R. Sherwood, and D. K. Ralston (2010), Sediment transport and deposition on a river-dominated tidal flat: an idealized model study, J. Geophys. Res., doi:10.1029/2010JC006248, in press.

Christie, M. C., and Dyer, K. R., 1998. Measurements of the turbid tidal edge over the Skeffling mudflats, in Black, K. S., Paterson, D. M., and Cramp, A. (eds) *Sedimentary Processes in the Intertidal Zone*, Geological Society, London, Special Publication, 139, 45-55.

Christie, M. C., Dyer, K. R., and Turner, P, 1999. Sediment flux and bed level measurements from a macro tidal mudflat, *Estuarine, Coastal and Shelf Sciences*, 49, 667-688.

Cortese, T. and Balachandar, S. 1995. High performance spectral simulation of turbulent flows in massively parallel machines with distributed memory. *International Journal of Supercomputer Applications*, 9 (3), 187–204.

Dalrymple, R. A., and P. L.-F. Liu (1978), Waves over soft mud: a two-layer model, *J. Phys. Oceanogr.*, pp. 1121-1131.

Elgar, S. and Raubenheimer, B. 2008. Wave dissipation by muddy seafloors, *Geophys. Reas. Lett.* 35, L07611, doi:10.1029/2008GL033245.

Ferry, J. and Balachandar, S., 2001, A fast Eulerian method for disperse two-phase flow, *Int. J. Multiphase Flow*, (27), 1199-1226.

Friedrichs, C.T., Aubrey, D.G., 1996. Uniform bottom shear stress and equilibrium hypsometry of intertidal flats. In: Pattiaratchi, C. (Ed.), Mixing in Estuaries and Coastal Seas. American Geophysical Union, Washington, DC, pp.405–429.

Hsu, T-J, Traykovski P. A., and Kineke, G. C., 2007. On modeling boundary layer and gravity driven fluid mud transport, *J. Geophys. Res.*, 112, C04011, doi:10.1029/2006JC003719.

Hsu T-J., C. E. Ozdemir, and P. A. Traykovski 2009, High resolution numerical modeling of wave-supported sediment gravity-driven mudflows. *J. Geophys. Res.* 114, C05014, doi:10.1029/2008JC005006

Lin, P. and Liu, P. L.-F., 1998. A numerical study of breaking waves in the surf zone. *J. Fluid Mech.*, Vol. 359, 239-264.

Mehta, A. J., 1989, On estuarine cohesive sediment suspension behavior, *J. Geophy. Res.*, 94(C10), 14303-14313.

Ozdemir, C. E., T.-J. Hsu, S. Balachandar, 2010a. Simulation of fine sediment transport in oscillatory boundary layer, *Journal of Hydro-environment Research*, 3, 247-259.

Ozdemir, C. E., Hsu, T.-J., Balachandar, S., 2010b. A numerical investigation of fine particle laden flow in oscillatory channel: the role of particle-induced density stratification, *J. Fluid Mech*., in press.

Sheremet, A. & G. W. Stone (2003). Observations of nearshore wave dissipation over muddy sea beds, *J. Geophy. Res*., 108 (C11): 3357.

Son, M., and Hsu, T.-J., 2008. Flocculation model of cohesive sediment using variable fractal dimension, *Environmental Fluid Mech*., 8, 55-71.

Son, M., and Hsu, T.-J., 2009. The effect of variable yield strength and variable fractal dimensional on flocculation of cohesive sediment, *Water Res*., 43, 3582-3592.

Son, M., and T.-J. Hsu, 2010a. Idealized study on cohesive sediment flux by tidal asymmetry, *Environmental Fluid Mechanics*, in press.

Son, M., and Hsu, T.-J., 2010b The effects of flocculation and bed erodibility on modeling cohesive sediment resuspension, *J. Geophys. Res*., submitted.

de Swart H. E., and J.T.F. Zimmerman, (2009). Morphodynamics of Tidal Inlet Systems, Annu. Rev. Fluid Mech., 41:203–29.

Torres-Freyermuth, A., and T.-J. Hsu, 2010. On the dynamics of wave-mud interaction: a numerical study, *Journal of Geophysical Research*, 115, C07014, doi:10.1029/2009JC005552.

Trowbridge, J. H., and G. C. Kineke (1994), Structure and dynamics of fluid mud on the Amazon continental shelf, J. Geophys. Res., 99, 865–874, doi:10.1029/93JC02860.

Winterwerp, J. C., and van Kesteren, W. G. M., 2004. Introduction to the physics of cohesive sediment in the marine environment. Elsevier.

PUBLICATIONS

1. Son, M., and Hsu, T.-J. 2008. Flocculation model of cohesive sediment using variable fractal dimension, *Environmental Fluid Mechanics*, 8, 55-71. [PUBLISHED, REFEREED]

2. Hsu T-J., C. E. Ozdemir, and P. A. Traykovski 2009. High resolution numerical modeling of wave-supported sediment gravity-driven mudflows *J. Geophys. Res*. 114, C05014, doi:10.1029/2008JC005006. [PUBLISHED, REFEREED]

3. Son, M., and T.-J. Hsu, (2009) The effect of variable yield strength and variable fractal dimension on flocculation of cohesive sediment, *Water Research*, 43, 3582-3592. [PUBLISHED, REFEREED]

4. Scott N. V., T.-J. Hsu, D. Cox, 2009. Steep wave, turbulence, and sediment concentration statistics and their implications to sediment transport, *Continental Shelf Research*, 29, 2303-2317. [PUBLISHED, REFEREED]

5. Yu, X, and T.-J. Hsu, and D. M. Hanes, 2010. Sediment transport under wave groups- the relative importance between wave shape and boundary layer streaming, *Journal of Geophysical Research*, 115, C02013, doi:10.1029/2009JC005348. [PUBLISHED, REFEREED].

6. Torres-Freyermuth, A., and T.-J. Hsu, 2010. On the dynamics of wave-mud interaction: a numerical study, *Journal of Geophysical Research*. 115, C07014, doi:10.1029/2009JC005552. [PUBLISHED, REFEREED]

7. Ozdemir, C. E., T.-J. Hsu, S. Balachandar, 2010. Simulation of fine sediment transport in oscillatory boundary layer, *Journal of Hydro-environment Research,* 3, 247-259. [PUBLISHED, REFEREED]

8. Ozdemir, C. E., Hsu, T.-J., Balachandar, S., 2010. A numerical investigation of fine particle laden flow in oscillatory channel: the role of particle-induced density stratification, *J. Fluid Mech.*[ACCEPTED]

9. Son, M., and T.-J. Hsu, 2010. Idealized study on cohesive sediment flux by tidal asymmetry, *Environmental Fluid Mechanics*. [ACCEPTED]

10. Son, M., and Hsu, T.-J., The effects of flocculation and bed erodibility on modeling cohesive sediment resuspension, *J. Geophys. Res*. [SUBMITTED]